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The Mineral Creek sulfide deposits are located in Allamakee County, Iowa on the extreme northwest fringe of the upper Mississippi Valley zinc-lead district. The ores consist of extensively weathered lead, zinc, and iron sulfides which were emplaced in areas of intense solution-collapse brecciation and along bedding plane and steeply-dipping longitudinal fractures. Mineralization appears to be localized on the crest of a NE-trending anticline, related to early Ordovician tectonism which affected NE Iowa and adjacent Wisconsin. Mineralogy and paragenesis of vein and hydrothermal alteration deposits at Mineral Creek are very similar to those of other fringe deposits in Iowa and Wisconsin. Much of the silicification (jasperoid) appears to be prehydrothermal.

INDEX DESCRIPTORS: Sulfide mineral deposits, hydrothermal alteration, northeast Iowa.

The Mineral Creek sulfide deposits are located about 16 km (ten miles) north of Waukon in Allamakee County, Iowa. They lie on the extreme northwest fringe of the upper Mississippi Valley zinc-lead district. Related deposits occur near Lansing in Allamakee County and in western Wisconsin, primarily north of the Wisconsin River (fig. 1). These scattered mineral deposits were all emplaced in host rocks of lower Ordovician and upper Cambrian age, notably in carbonates of the Oneota Formation. In contrast, main district ores were emplaced in younger, middle Ordovician carbonate rocks (Heyl, *et al,* 1959).

The purpose of this study is to provide information about the nature and origin of hydrothermal deposits in Cambro-Ordovician host rocks. Mounting evidence indicates ore-forming fluids in the main upper Mississippi Valley zinc-lead district moved upward through a vertical plumbing system, first passing through Cambro-Ordovician hosts. The underlying rocks and rock structures may have exerted control on the character and distribution of main-district deposits (Heyl, *et al,* 1959, Heyl 1968, Ludvigson and Garvin, 1981).

Lead was mined at Mineral Creek during 1856-57 from small workings on the east and west sides of a small tributary to Mineral Creek (S½ Sec. 13, T99N, R6W) (Calvin, 1894). The workings consist of short (less than 18 meters [60 feet]) horizontal to somewhat downward-inclined drifts. Because of the low grade and spotty distribution of the ore, and the toughness of the enclosing wall rock, mining was limited and of short duration.

According to Heyl, *et al* (1959), only about 100,000 lbs of galena concentrate were taken from the mines during the two years of operation. Prospect drilling was done in 1943, but economic lead-zinc concentrations were not encountered.

The ore deposits at Mineral Creek have been briefly described by Calvin (1894), Leonard (1896), and Heyl, *et al* (1959). The location of mine maps apparently made during the 1940's is unknown. Ludvigson (1976) studied the mines and general geology of the region in conjunction with a regional study of LANDSAT linears. Detailed studies of the sulfide mineralization and hydrothermal alteration have not been previously reported.

Despite the long period of inactivity, three of the Mineral Creek Mines are still accessible. These occur on the east side of the tributary valley, where their locations are marked by clusters of birch trees which have grown around the adits since the time of mining. Workings on the west side of the valley have collapsed and are inaccessible. The mines investigated in this report have been numbered 1, 2, 3, southward from the Clem Byrnes property access (Ludvigson, 1976). Mine No. 3 is very small and difficult to enter; hence, it was not studied in detail. Mines No. 1 and No. 2 were mapped with Brunton and tape and were studied extensively. The adit to Mine No. 1 is near the level of an adjacent intermittent stream bed. Storm and snow-melt runoff have repeatedly flooded the workings, coating the walls with mud and depositing a decimeter or more of silt on the floors of the lower drifts. As a result, the geology of the lower level is somewhat obscure and access in places is difficult.

GENERAL GEOLOGY

The ore deposits at Mineral Creek occur in carbonate rocks of the Hager City member of the Oneota Formation (fig. 2). A concise summary of the stratigraphy and petrology of the Prairie du Chien group in NE Iowa is given by Ludvigson (1976). The Hager City at Mineral Creek is a medium gray-brown saccharoidal dolomite containing nodules and thin beds of chert. The chert characteristically contains well-preserved oölites and the occasional remains of small fossils, particularly gastropods. It is frequently chalky due to partial dissolution and replacement by dolomite. The Hager City also contains abundant solution collapse breccia resulting from karstification of the dolomite prior to deposition of the overlying St. Peter Sandstone (Ludvigson, 1976).

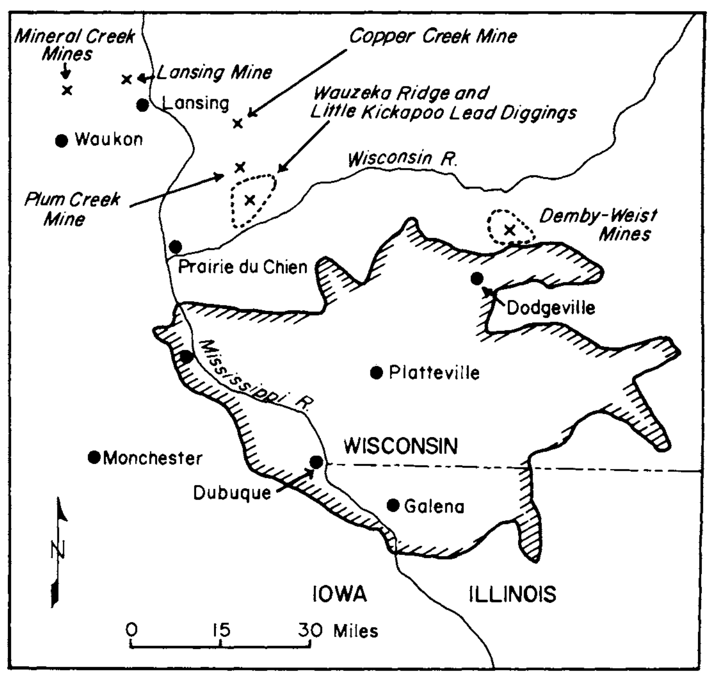

Fig. 1. The Upper Mississippi Valley zinc-lead district and its proximity to the Mineral Creek and related deposits. (Modified from Heyl, *et al,* 1959.)

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ORE DEPOSITS

Form and Structure

The sulfide deposits at Mineral Creek occur in small brecciated zones within the Hager City Dolomite. Investigatons by Heyl, *et al* (1959) did not identify any consistent fracture trends. Brecciation of the host carbonate rocks makes identification of trends difficult. A detailed investigation of the mines reveals areas of uninterrupted bedding among the zones of brecciation (fig. 3). In Mine No. 1 fractures of two types can be observed: 1) gently-dipping bedding-plane fractures, and 2) steeply-dipping to nearly vertical fractures. These fractures are best seen in the backs of drifts and stopes, and where they are accentuated by mineralization. Although limited exposure and tight quarters permitted measurement of only approximate strikes and dips of the fractures, it is clear that bedding plane fractures strike northeast to nearly east. Bed attitudes were plotted on a map of the upper and lower levels of Mine No. 1 (fig. 4). It is evident that the attitudes define an anticline whose axial plane strikes northeast and whose flanks dip as much as 20° (fig. 5). Although fewer measurements were taken at Mine No. 2, bed attitudes also suggest the same northeast-trending anticline. It is significant that the anticlinal crest lies within the working areas of the two mines. The steeply-dipping fractures were best observed in Mine No. 1. All strike approximately parallel to the anticlinal axis and dip toward it or are vertical. This orientation suggests that they developed as release-type tension fractures in response to bending of the dolomite strata during the latest stage of anticline formation.

Hydrothermal mineralization at Mineral Creek is localized in zones of greatest brecciation and within the fractures previously described. Fracture fillings are short, discontinuous, and sometimes lens-like. The lenses may be several decimeters across. In Mine No. 2 one lens is 2.5 meters (8 feet) long and attains a maximum thickness of 45 centimeters (18 inches). The abundance of well-formed calcite scalenohedra in the lenses indicates that in places the plumbing was quite open. In other places early iron sulfide deposition healed fractures, cutting them off from subsequent fluid migration.

Ore Mineralogy

The ore deposits presently lie within the vadose zone and are extensively altered by chemical weathering. The only primary sulfide which is relatively unaltered is galena. Fortunately much of the replacement of sulfides is pseudomorphic; hence, primary mineralogy can be deduced with relative ease.

The ore mineralogy is similar to that in the main district. Galena, rimmed by cerussite and anglesite, occurs in single octahedral and cubo-octahedral crystals and in small subhedral clusters. Early cubic galena, recognized by Heyl, *et al* (1959) in the main district was not observed at Mineral Creek. Sphalerite, almost completely replaced by smithsonite and hemimorphite, is present in thin, finely crystallized bands of colloform habit. Where the bands are unreplaced, the sphalerite is generally pale-colored. In the main district sphalerite of this color and habit was deposited relatively late in the paragenetic sequence (Heyl, *et al,* 1959). Early dark sphalerite was not observed at Mineral Creek, but it may have been destroyed by weathering. Marcasite, pseudomorphically altered to goethite, occurs as single blades and complex twins and intergrowths. Pyrite, also replaced by goethite, is present in two forms. A few tiny octahedra may be scattered directly on wall rock surfaces. Colloform or "sooty" pyrite, well known in the main district, is also present at Mineral Creek. Pseudomorphic replacement by goethite remarkably has preserved this fragile fabric. Relict banding and radial structure of the original pyrite can be seen locally. Pyrite may have been disseminated in the host carbonate rock as it is in the main district, but if so it has been destroyed by weathering. The only primary non-sulfide mineral observed at Mineral Creek (excluding wall-rock alteration minerals) is

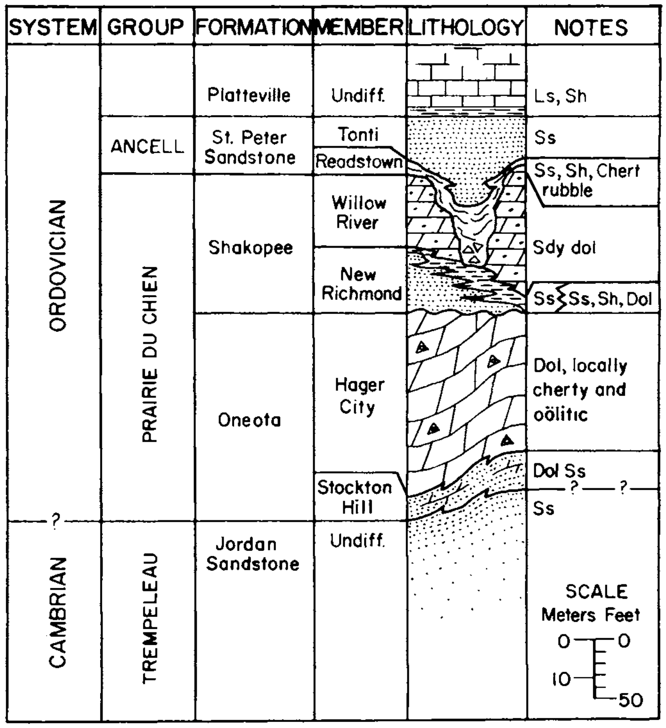

Fig. 2. Lithostratigraphy of the Prairie du Chien Group and adjacent stratigraphic units. (After Ludvigson and McAdams, 1980.)

light amber to white calcite, which is found in modified scalenohedra (probably Type 3 calcite of Heyl, *et al* [1959]) up to several centimeters in length which project into open vugs, or in massive sparry fracture fillings. Crystal surfaces are commonly etched accentuating cleavage cracks.

Ore Mineral Paragenesis

Ore mineral paragenesis at Mineral Creek closely parallels that in the main district. Marcasite and octahedral pyrite were deposited on and within the host rock. Sphalerite, colloform pyrite and galena were deposited next. Sphalerite encloses both pyrite and galena, hence its deposition spans that of the other two sulfides. Depositional relations between colloform pyrite and galena could not be determined. Calcite (Type 3 of Heyl, *et al,* 1959) was deposited last, lining or filling vugs in which sulfides were previously deposited. Ore mineral parageneses for Mineral Creek and the main district are compared in figure 6.

WALL ROCK ALTERATION

Description of Alteration Types

Hydrothermal alteration at Mineral Creek and other deposits in the Prairie du Chien group is characterized by solution, dolomitization, silicification, and probably pyritization. Minor amounts of a greenish alteration mineral, tentatively identifed by Heyl, *et al* (1959) as celadonite, also occurs at Mineral Creek. The amount of this mineral was insufficient for optical or x-ray confirmation. Sericite, reported at the Demby-Weist mines in Wisconsin (Heyl, *et al,* 1959) was not observed at Mineral Creek.

Hydrothermal solution of the carbonate rocks of the Hager City Dolomite is abundant. It is evidenced by irregular pockets a few millimeters to more than a centimeter across. Solution was controlled by bedding plane and other fractures and by initial bed-controlled differences in rock permeability. Its effect was to greatly increase the permeability of the wall rock, thus affording access to later migrating ore fluids. Quartz, dolomite, and sulfides commonly line or fill these solution voids.

Hydrothermal dolomitization is abundant and pervasive at Mineral Creek, as elsewhere in the district. Heyl's *et al* (1959) color distinction between hydrothermal and prehydrothermal dolomite (pinkish-brown - hydrothermal; gray-brown - prehydrothermal) is not reliable at Mineral Creek. All dolomite here is gray-brown. The most reliable criteria for distinguishing hydrothermal from prehydrothermal dolomite are grain size and zoning. Hydrothermal dolomite is quite coarse and euhedral, especially where lining solution cavities or where scattered in quartz. Euhedral crystals are commonly zoned. Coarse, zoned, euhedral, hydrothermal dolomite crystals occur locally in a matrix of fine equigranular prehydrothermal dolomite. Aggregations of these coarse crystals produce a somewhat mottled texture. Occasional oölitic structures preserved during prehydrothermal (early diagenetic?) regional dolomitization may be partly to completely enclosed by large hydrothermal dolomite crystals. This recrystallization has resulted in a kind of poikilotopic relationship. The above-described distinctions are subtle and generally recognizable only in thin section.

Hydrothermal silicification is generally abundant in the upper Mississippi Valley zinc-lead district in wall rocks of the Prairie du Chien Group (Heyl, *et al*, 1959). At Mineral Creek the silica occurs in several forms. In describing these forms, to minimize the confusion often caused by terms such as jasperoid, chert, and chalcedony, I have used descriptive terms similar to those used by Biggs (1957) and Orme (1974). The forms of silica (quartz) at Mineral Creek are: 1) cryptocrystalline (C-quartz), 2) microcrystalline (M-quartz), 3) fibrous or chalcedonic (F-quartz), and 4) macrocrystalline or drusy (D-quartz) (figs. 7-12).

C-quartz occurs as replacement of oölites and fecal pellets, and in

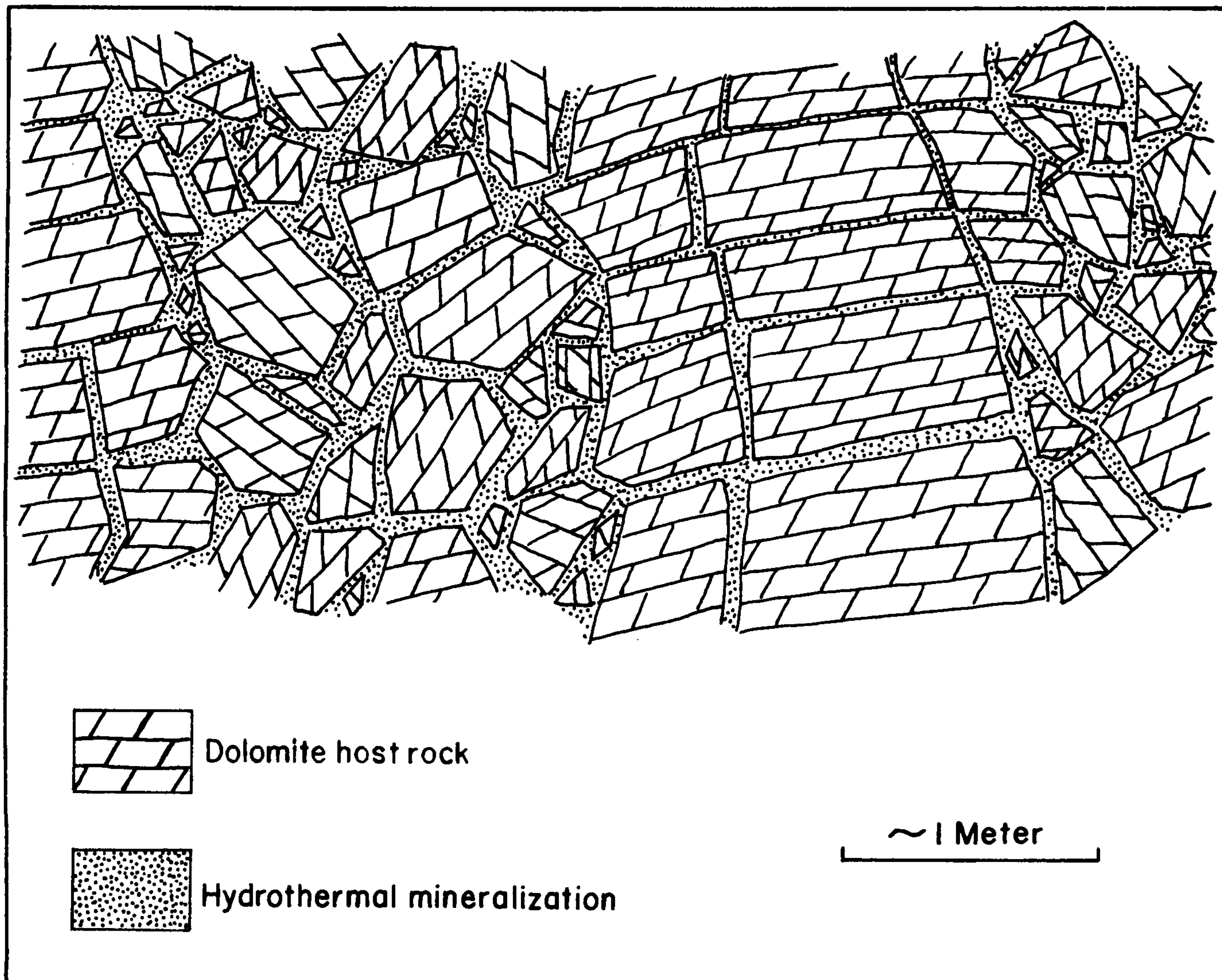

Fig. 3. Idealized sketch of mineralized solution collapse structures and adjacent uninterrupted bedding, Mineral Creek Mine No. 2.

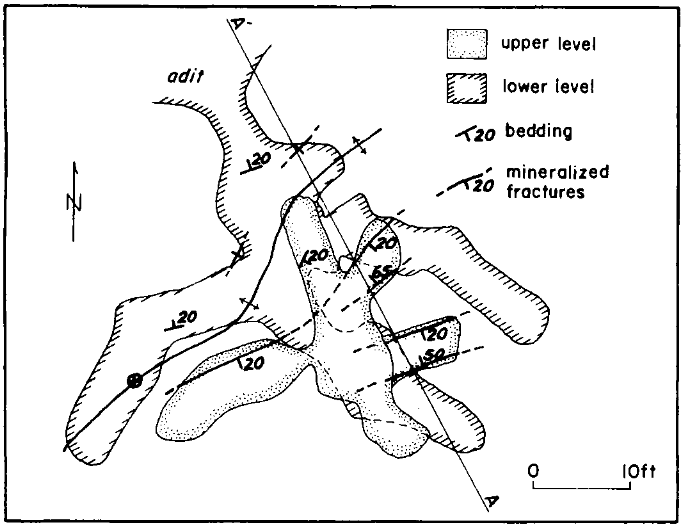

Fig. 4. Upper and lower workings of Mineral Creek Mine No. 1 showing bed attitudes and associated structure.

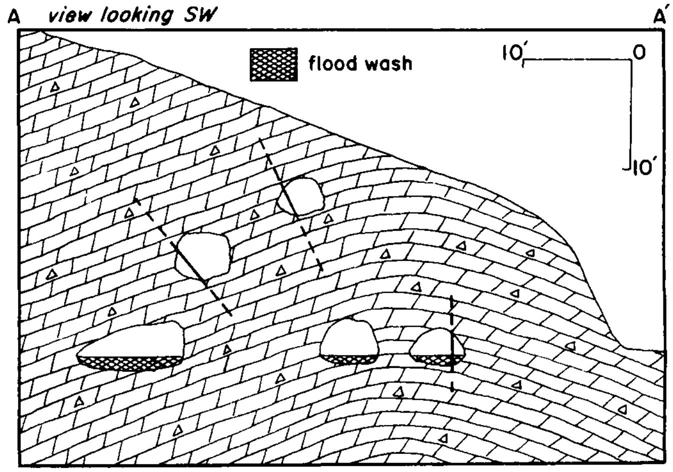

Fig. 5. Geologic cross-section of Mineral Creek Mine No. 1 along A - A' (see Fig. 4) showing anticlinal structure. Areas of breccia-tion not shown.

irregular structureless masses. Optically, it is nearly isotropic and may contain minute inclusions of gas, fluid, or foreign material. It is more or less chalky due to dissolution and replacement by dolomite.

M-quartz occurs as interstitial fillings between C-quartz oölites, as linings of solution cavities and fracture openings, as replacement of fossil shells (particularly brachiopods and gastropods) and occasionally within oölites. It grades into C-quartz, F-quartz, or D-quartz. Where lining open cavities, it generally coarsens inward to D-quartz.

F-quartz exhibits typical banded, colloform, and in some cases spherulitic habit. It often displays possible shrinkage cracks, suggesting colloidal origin. It is interlayered with M-quartz in cavity linings and occurs as islands in dolomite. Textural relations of the latter association (the most common) indicate replacement of quartz by dolomite, the islands being unreplaced remnants.

D-quartz occurs as linings or fillings of solution cavities or fracture openings. Where filling of cavities is incomplete, the quartz shows the usual euhedral terminations. D-quartz often stands out as fresh veinlets in chalky C-quartz and M-quartz.

Pyritization (or marcasitization) probably occurred at Mineral Creek mines, but oxidization has destroyed the original fine-grained sulfide material. Occasionally, small isolated rust spots are observed in dolomite, indicating former FeS_2 impregnations. Nearby, along Mineral Creek valley (SW¼ Sec 23, T99N, R6W), outcrops of highly silicified St. Peter Sandstone can be observed. The gray to almost black color of the hydrothermally recrystallized sandstone is due to finely-divided FeS_2.

Paragenesis of Alteration

Determining the sequence of events in the hydrothermal alteration of wall rock at Mineral Creek is complicated by the fact that more than one generation of a given alteration mineral may be present. Relations between prehydrothermal and hydrothermal dolomite were discussed earlier. Understanding the paragenesis of quartz types is even more difficult. Not all the quartz is hydrothermal, in fact, much of it may be prehydrothermal. The evidences from the present study are:

1. The quartz frequently occurs in nodular form. The smooth outlines of the nodules are often corroded in places because of replacement by dolomite. These appear to be chert nodules, typical of many carbonate rock sequences, and observed at other places in the district.
2. C-quartz and M-quartz frequently replace oölites. In some cases replacement is good enough to preserve concentric banding. Yet, oölites are rare in adjacent dolomite, and where present are poorly preserved. Since the Hager City underwent early regional dolomitization, the preservation of the oölites indicates silicification prior to dolomitization.
3. Fossil remains, like the oölites, are almost exclusively restricted to areas of silicification, thus they also indicate silicification prior to dolomitization.
4. Breccia clasts in solution collapse pockets include silicified material. Silicification here clearly predates collapse, which

	UPPER MISSISSIPPI VALLEY DISTRICT	MINERAL CREEK MINES
MINERAL	EARLY → LATE	EARLY → LATE
Quartz	—	—
Dolomite	—	—
Pyrite	——	oct col
Marcasite	—— - -	- - -
Sphalerite	——	——
Chalcopyrite	——	N.O.
Barite	— —	N.O.
Galena	——	——
Calcite	——	——

Fig. 6. Comparison of major primary minerals and mineral parageneses for the Mineral Creek Mines and the Upper Mississippi Valley Zn-Pb district. N.O. = not observed; oct = octahedral; col = colloform. (Data for district from Heyl, 1968.)

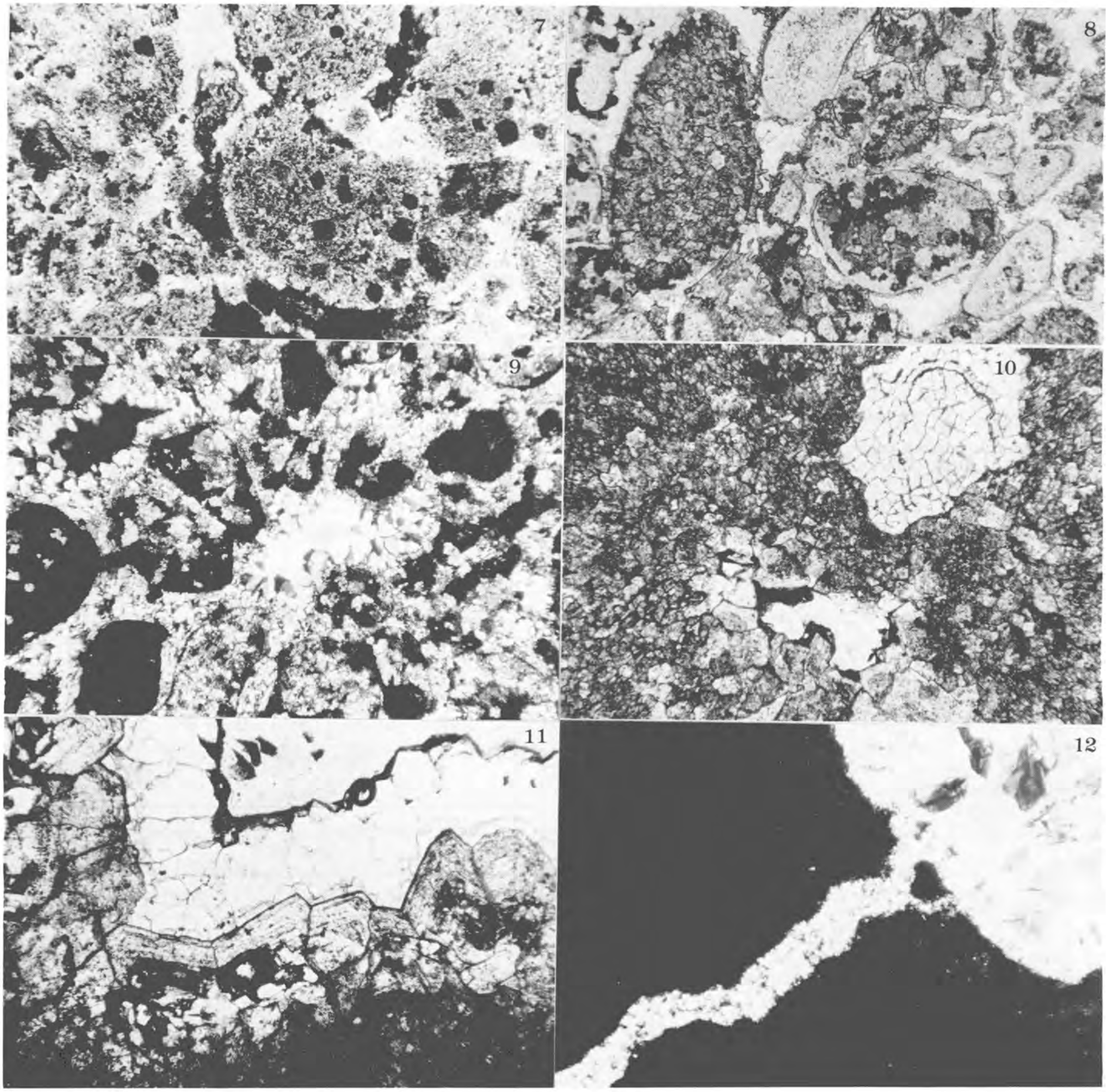

Fig. 7-12. Photomicrographs of thin sections showing quartz types and quartz-dolomite relations at Mineral Creek mines. For all figures bar length └──┘ = 0.1 mm. Fig. 7. C-quartz oölites and pellets (mottled gray), M-quartz interstitial filling (white), C-quartz partly replaced by dolomite (black rhombs); (plane light). Fig. 8. Dolomite (mottled gray) replacing C-quartz oölites and pellets (uniform light gray), unreplaced M-quartz (white); (plane light). Fig. 9. Partly dolomitized C-quartz (black), M-quartz vug linings and fillings (white and light gray); note open vug lined in quartz at upper left; (X-polarized light). Fig. 10. F-quartz island (upper right) in dolomite; note possible shrinkage cracks in F-quartz and vug lined with large dolomite crystals; (plane light). Fig. 11. Large open vug in dolomite (bottom) lined with zoned euhedral dolomite (gray), in turn covered with euhedral D-quartz (white); (plane light). Fig. 12. Vug and fracture in dolomite (black) filled with M-quartz; (X-polarized light).

long predated hydrothermal activity.

5. The chalky nature of much of the quartz is due to dissolution and replacement by dolomite. The fine-grained nature and lack of zoned euhedral crystals in some of the replacing dolomite indicates that this dolomite is prehydrothermal.
6. The islands of spherulitic F-quartz and M-quartz appear to be replaced by fine-grained, prehydrothermal dolomite.

That quartz which seems clearly to be hydrothermal is the M-quartz, banded F-quartz, and D-quartz which lines or fills cavities and fractures in dolomite and earlier quartz. The generally fresh appearance of the fillings, compared to the chalky nature of the enclosing dolomite-invaded quartz matrix help distinguish the hydrothermal from the prehydrothermal varieties.

The sequence of important events preceding and during the hydrothermal alteration of host rocks at Mineral Creek is outlined below. Evidences for structural and geomorphic events have been discussed by Heyl, *et al* (1959) and Ludvigson and McAdams (1980). Evidences for depositional events were presented earlier in this paper.

1. prehydrothermal silicification of limestone, preserving oölites and fossil structures (all C-quartz and much M-quartz and F-quartz).
2. prehydrothermal regional dolomitization, which partly replaced earlier quartz. Oölites in all stages of replacement by dolomite can be seen at Mineral Creek.
3. pre-Shakopee folding and fracturing of Hager City Dolomite.
4. karstification and brecciation of Hager City Dolomite.
5. hydrothermal solution of dolomite and fracturing of dolomite and quartz.
6. post-Ordovician folding and fracturing of Hager City Dolomite.
7. hydrothermal dolomitization, producing crystal-lined vugs and replacing to varying degrees earlier dolomite and quartz.
8. hydrothermal silicification which produced banded cavity linings and fillings of M-quartz, F-quartz, and D-quartz. It is possible that this stage of silicification involved some remobilization of earlier quartz.
9. late-stage hydrothermal dolomitization which deposited zoned euhedral crystals on D-quartz cavity linings.
10. hydrothermal pyritization.

RELATION BETWEEN MINERAL CREEK ORE DEPOSITS AND OTHER DEPOSITS IN PRAIRIE DU CHIEN AND UPPER CAMBRIAN HOSTS

Sulfide ore deposits which are closely related to those at Mineral Creek occur a short distance west of Lansing, Iowa in Allamakee County (NW¼ Sec. 10, T99N, R4W), and at several localities in west-central Wisconsin, primarily north of the Wisconsin River. The Wisconsin deposits include the Wauzeka Ridge and Little Kickapoo lead diggings and the Plum Creek and Copper Creek copper deposits in Crawford County, and the Demby-Weist lead deposits in Iowa County. These occurrences are described briefly in Heyl, *et al* (1959) and Ludvigson (1976). All of the above-mentioned deposits, like those at Mineral Creek, were emplaced in the Hager City Dolomite directly beneath its unconformable contact with the new Richmond Sandstone. The Lansing and Demby-Weist deposits are reported to extend downward into upper Cambrian siliceous clastic rocks (Heyl, *et al*, 1959). Earlier studies in the district indicate that vein and alteration mineralogies and parageneses of all of these deposits are very similar. Ludvigson and McAdams (1980) suggest that mineralization was controlled by structures produced by an N-S-trending pre-Shakopee compressive stress field. The Lansing deposits represent fillings of N-S vertical extension fractures, the Demby-Weist deposits fillings of one set of conjugate shears (NW), and the Little Kickapoo, Wauzeka Ridge, and perhaps the Copper Creek deposits, fillings of tension fractures parallel to E-W to E-NE trending fold axes. Results of the present study of structural controls on ore deposition at the Mineral Creek mines is consistent with this general interpretation. Concentrations of tension fractures at anticlinal crests controlled subsequent pre-St. Peter karst development and associated collapse brecciation. This pre-Shakopee tectonic and subsequent solutional activity provided open passageways for vertically-ascending ore fluids, which localized deposition in areas of greatest brecciation. Exploration for lead-zinc deposits elsewhere in the fringe area as well as in Prairie du Chien rocks beneath the main district should consider the crests of E-W- to NE-trending folds buried beneath the Shakopee-Oneota unconformity.

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